

SOLAR-LIKE OSCILLATIONS OF SEMIREGULAR VARIABLES

J. CHRISTENSEN-DALSGAARD^{1,2}, H. KJELDSSEN², J. A. MATTEI³

¹Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark; jcd@ifau.dk

²Teoretisk Astrofysik Center, Danmarks Grundforskningsfond; hans@ifau.dk

³American Association of Variable Star Observers, 25 Birch St., Cambridge, MA 02138, USA;
 jmattei@aaavso.org

Astrophys. J. Lett., revised, February 1, 2008

ABSTRACT

Oscillations of the Sun and solar-like stars are believed to be excited stochastically by convection near the stellar surface. Theoretical modeling predicts that the resulting amplitude increases rapidly with the luminosity of the star. Thus one might expect oscillations of substantial amplitudes in red giants with high luminosities and vigorous convection. Here we present evidence that such oscillations may in fact have been detected in the so-called semiregular variables, extensive observations of which have been made by amateur astronomers in the American Association for Variable Star Observers (AAVSO). This may offer a new opportunity for studying the physical processes that give rise to the oscillations, possibly leading to further information about the properties of convection in these stars.

Subject headings: convection – supergiants – stars: variables: other – stars: oscillations

1. INTRODUCTION

There is strong evidence that the observed solar oscillations are intrinsically stable but excited stochastically by the turbulent convection in the near-surface layers. Stability calculations that take the interaction with convection into account generally find linear stability (e.g. Balmforth 1992a); also, it would be difficult to account for the observed very low amplitudes if the modes had been unstable (Kumar & Goldreich 1989). On the other hand, calculations based on a mixing-length formulation (Balmforth 1992b) or detailed hydrodynamical simulations of convection (e.g. Stein & Nordlund 1998, 2001) have obtained energy input from stochastic convective excitation that appears consistent with the observed oscillation amplitudes and damping rates. Also, the observed distribution of mode amplitudes (e.g. Chaplin et al. 1997) is essentially consistent with theoretical expectations assuming this excitation mechanism (Chang & Gough 1998).

On this basis one may try to predict amplitudes of similar oscillations in other stars. Early simple estimates by Christensen-Dalsgaard & Frandsen (1983) indicated that the amplitudes increase with effective temperature along the main sequence, and also increase rapidly with increasing luminosity. These estimates have recently been confirmed by more detailed calculations, although still based on a mixing-length formalism, by Houdek et al. (1999). In the present context it is particularly noteworthy that Christensen-Dalsgaard & Frandsen predicted quite substantial amplitudes for stars on the red-giant branch.

The predicted amplitudes for main-sequence stars are very low; a few parts per million in intensity or of order 1 m s^{-1} in radial velocity. Thus it is hardly surprising that little evidence is available for solar-like oscillations in stars near the main sequence. Brown et al. (1991) found indications of solar-like power in Procyon. This was recently confirmed by Martić et al. (1999) and Barban et al. (1999) who, however, noted that the inferred amplitude was smaller by about a factor of 3 than the predictions

of Houdek et al. (1999). Kjeldsen et al. (1995) detected oscillations in the equivalent widths of Balmer lines in the subgiant η Boo, at amplitudes which were not inconsistent with the theoretical expectations; however, Brown et al. (1997) were unable to confirm these oscillations in Doppler-velocity observations. Gilliland et al. (1993) made an extensive search for solar-like oscillations in stars in the open cluster M67, but with no positive detections; in several cases they obtained upper limits to the amplitudes substantially below the theoretical predictions. For the solar near-twin α Cen A Kjeldsen et al. (1999) failed to find definite oscillations, although the upper limit was again consistent with expectations. However, Schou & Buzasi (2001) found clear evidence for oscillations in photometric observations of α Cen A from the WIRE satellite, with amplitudes slightly higher than solar, as expected. Finally, Bedding et al. (2001) very recently made a definite detection of solar-like oscillations in the sub-giant β Hyi, while Bouchy & Carrier (2001) obtained a strikingly clear signal of oscillations in α Cen A, in both cases with amplitudes close to the expected. Evidently, the observational situation for stars near the main sequence is improving, while the theoretical understanding is still rather uncertain.

For giant stars, larger amplitudes are expected. Indeed, Arcturus (of spectral type K1.5III) has been found to show oscillations that are plausibly of solar-like nature (Smith, McMillan & Merline 1987; Innis et al. 1988; Merline 1998). Similar oscillations have also been found in luminosity observations of K giants in 47 Tuc (Edmonds & Gilliland 1996), and in radial-velocity observations of a sample of K and M giants and supergiants (Cumplings et al. 1998). Finally, Buzasi et al. (2000) found possible evidence for solar-like oscillations in the moderate red giant α UMa.

For even more luminous red giants quite substantial amplitudes, possibly reaching several tenths of a magnitude, are expected. Studies of these stars are complicated, however, by the fact that periods of the order of several months or even years are expected, requiring very ex-

tended observations which are generally not available from professional investigations. It is therefore extremely fortunate that the American Association of Variable Star Observers (AAVSO) has a very extensive database on large-amplitude, long-period pulsators. In this letter, we analyze a sample of such stars to argue that they do indeed show evidence for stochastically excited, solar-like oscillations.

2. OBSERVATIONS OF SEMIREGULAR VARIABLES

The observations were obtained from the AAVSO archives, in most cases extending over 30 – 40 years; although more extensive data are available, these are so far the longest sequences that have been validated and analyzed in detail. The CLEANest algorithm (Foster 1995) was used, involving least-squares fitting of the data to sinusoids taking into account the possible presence of multiple periods. The data were analyzed over windows of typical lengths of a few thousand days, hence providing measures of the periods $P(t)$ and amplitudes $A(t)$ as functions of time t . From this we can in particular determine the mean $\langle A \rangle$ and the root-mean-square standard deviation $\sigma(A)$ of the amplitudes.

Some results are illustrated in Fig. 1. As noted already by Mattei et al. (1997) there is a clear division in this diagram, between the Mira variables with large amplitudes and small amplitude scatter and the semiregular (SR) variables with relatively low amplitudes and large scatter. Also, it is striking that there appears to be a strong correlation, in the latter group, between A and $\sigma(A)$, whereas no such correlation is found for the Miras. This correlation is the main piece of evidence which we consider in the following.

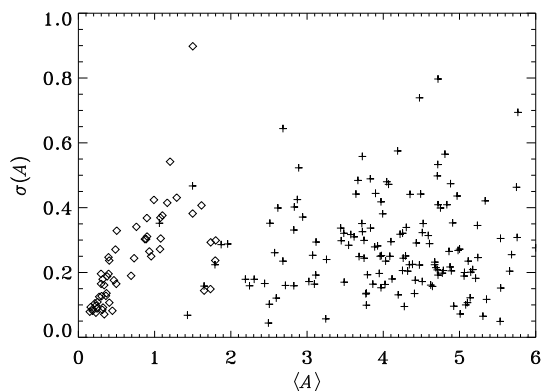


FIG. 1.— Properties of long-period variables, from AAVSO observations analyzed with the CLEANest algorithm. The abscissa is amplitude A in visual magnitude, and the ordinate is the root-mean-square scatter in the amplitude. Crosses and diamonds show stars that have been classified as Mira variables and semiregular variables, respectively. Adapted from Mattei et al. (1997).

3. PROPERTIES OF STOCHASTICALLY EXCITED OSCILLATORS

The statistical properties of stochastically excited oscillations were discussed, for example, by Kumar, Franklin & Goldreich (1988) and Chang & Gough (1998). If the modes are observed over a time short compared with the

damping time, the energy distribution is exponential, leading to the following distribution for the amplitude A :

$$p(A) = \frac{2A}{\mathcal{A}^2} \exp\left(-\frac{A^2}{\mathcal{A}^2}\right), \quad (1)$$

where the average pulsation energy is proportional to \mathcal{A}^2 . The observed amplitudes of solar oscillation satisfy this distribution quite accurately (e.g. Chaplin et al. 1997). According to Eq. (1) the average $\langle A \rangle$ and standard deviation $\sigma(A)$ of the amplitude are determined by $\langle A \rangle = (\sqrt{\pi}/2)\mathcal{A}$, $\sigma^2(A) = \langle A^2 \rangle - \langle A \rangle^2 = (1 - \pi/4)\mathcal{A}^2$, and hence

$$\sigma(A) = \left(\frac{4}{\pi} - 1\right)^{1/2} \langle A \rangle \simeq 0.52 \langle A \rangle. \quad (2)$$

To illustrate this behavior, we have computed a set of artificial data simulating a stochastically excited oscillator with a period of 82 days. The simulation is in addition characterized by the sampling-time interval Δt , the damping time τ_d and the average excitation δA at each sampling time. The signal is written as $A_1(t) \sin(\omega t) + A_2(t) \cos(\omega t)$, where ω is the angular frequency corresponding to the period. At each sampling time the amplitudes A_1 and A_2 are reset, according to

$$A_i(t + \Delta t) = \exp(-\Delta t/\tau_d) A_i(t) + \delta A \mathcal{N}_i, \quad (3)$$

where \mathcal{N}_i is a normally distributed random variable with zero mean and unit variance. The ‘data’ cover a total period of around 1600 years. They were analyzed in segments of 1 year, to determine the total power \mathcal{P}_i for each segment which was used as an estimate of the mode energy; the energy, normalized to its average, was then determined as $E_i/\langle E \rangle = \mathcal{P}_i/\langle \mathcal{P} \rangle$, where the average is over the segments. The mean and standard deviation of the amplitudes, estimated by $\sqrt{\mathcal{P}_i}$, were similarly evaluated.

Figure 2 shows an example of a simulated timestring, together with the distribution of inferred mode energies, binned and suitably normalized (cf. Chang & Gough 1998) to make it directly comparable with the exponential distribution $\exp(-E/\langle E \rangle)$ which is also shown. It is evident that the data do indeed approximately satisfy the exponential distribution of energy. For this sample, we find $\sigma(A)/\langle A \rangle = 0.49$, in reasonable agreement with Eq. (2).

4. RESULTS AND DISCUSSION

According to Eq. (2) there is a direct relation between the value and scatter of the amplitude for stochastically excited oscillators. This is clearly reminiscent of the correlation observed in Fig. 1 amongst the SR variables. To make a more detailed comparison, we show results for these variables again in Fig. 3, together with the relation (2). It is evident that the observed and predicted behavior are indeed quite similar. Thus it is plausible that the observed oscillations are excited in this manner.

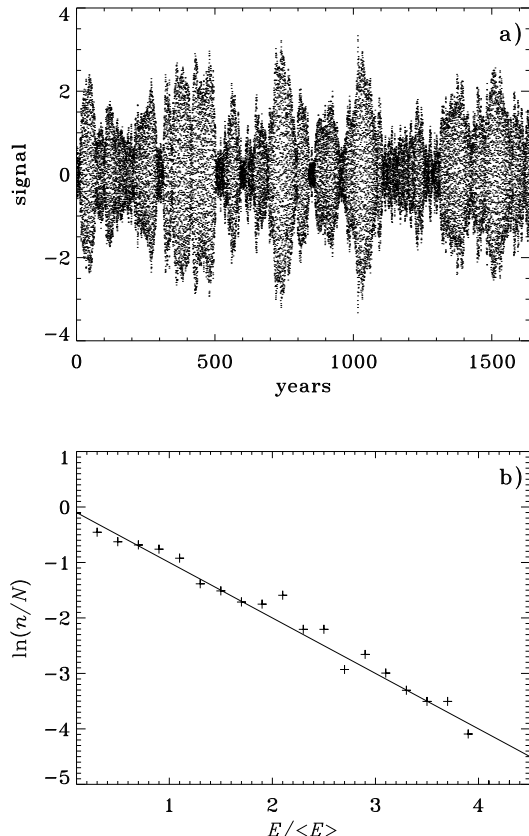


FIG. 2.— Artificial time series for an oscillation with a period of 82 days, a damping time τ_d of 60 years and a sampling-time interval Δt of 20 days, computed according to Eq. (3). The top panel shows the computed time series which, as indicated, covers about 1600 years. In the bottom panel the points show the binned, normalized distribution of mode energy, in units of the mean energy; the line corresponds to the expected exponential distribution in Eq. (1) (for further details, see Chang & Gough 1998).

In the case of the Sun, and the carefully observed K giant Arcturus, a substantial number of modes are observed to be excited, as would indeed be expected given the broad-band nature of the stochastic forcing. Christensen-Dalsgaard & Frandsen (1983) noted that the number of available modes decreases in very luminous giant stars where the acoustical cut-off frequency, which likely provides an upper limit to the observable spectrum, approaches the frequency of the fundamental radial mode. Even so, it is encouraging that most of the SR variables appear to be at least double-periodic (Mattei et al. 1997).

Further analyses are required to reach a definite conclusion on the nature of these stars. Additional scatter in the inferred amplitudes might arise from beating between unresolved frequencies in the spectra of the stars. On the other hand, it was noted by Kumar et al. (1988) that the amplitude distribution becomes more peaked, reducing the scatter, if the observing time is not short compared with the (in this case entirely unknown) lifetime of the modes. An additional effect may arise because of the large amplitudes of the oscillations. Indeed, it is likely that for the SR variables, as for the Mira variables, the amplitude in the visible region of the spectrum is strongly enhanced by at-

mospheric effects. By comparing the AAVSO amplitudes with the bolometric amplitudes obtained from Whitelock, Marang & Feast (2000), for the stars common between the two samples, we find that the visual amplitudes are on average larger by a factor 5 – 6 than the bolometric amplitudes. This may cause a nonlinear relation between the underlying pulsations and the observed response, possibly involving saturation at the highest amplitudes. To model this we have carried out additional analyses of the simulated timestring shown in Fig. 2a, after filtering with a suitably scaled \sinh^{-1} response. It was found that such saturation reduced the scatter quite substantially: even if the maximum amplitude was reduced by only 17 per cent, relative to the linear response, $\sigma(A)/\langle A \rangle$ was reduced from the value of 0.49 found in the linear case to 0.47. There is indeed some hint that the observed values are below the linear trend at higher amplitudes, in accordance with this mechanism.

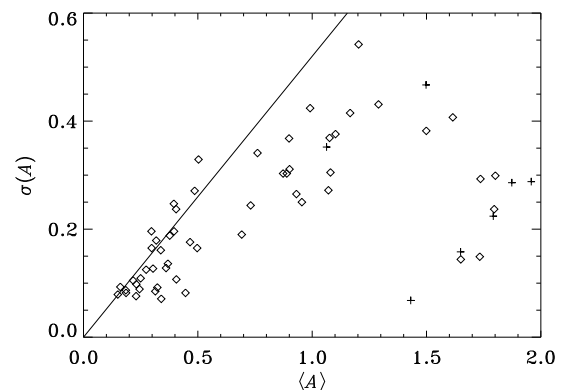


FIG. 3.— Root-mean-square scatter in the amplitude against amplitude, for the low-amplitude sample of AAVSO stars (see also Fig. 1). Crosses and diamonds show stars that have been classified as Mira variables and semiregular variables, respectively. The solid line shows the theoretical relation for stochastically excited oscillators, from Eq. (2).

The amplitudes found for the semiregular variables range as high as around 1.5 magnitude in the visual (cf. Fig. 3). Assuming the scaling between visual and bolometric amplitudes mentioned above, this corresponds to an amplitude in relative luminosity variations $\delta L/L$ of around 0.3, roughly five orders of magnitude higher than observed in the Sun. No estimates have so far been made of amplitudes of specific stars in this group. Based on the calculations by Christensen-Dalsgaard & Frandsen (1983), Kjeldsen & Bedding (1995) estimated that $\delta L/L$ scales as $LM^{-1}T_{\text{eff}}^{-1}$, where L , M and T_{eff} are luminosity, mass and effective temperature of the star. The validity of extrapolating this relation to the parameter range of the semiregular variables is perhaps somewhat doubtful; also, the parameters of these stars, particularly their mass, are uncertain. However, the amplitudes observed are at least not obviously inconsistent with the estimates based on the scaling relation.

5. CONCLUSIONS

At present we have secure observational information about very few stochastically excited pulsating stars, and hence additional information about this kind of pulsation, for a broad range of stars, would be extremely valuable, as a test for our models of the excitation. With a better physical understanding of the excitation mechanism the properties of the oscillations may also provide interesting diagnostics of the properties of convection, as a supplement to direct observations of velocity and intensity effects of surface convection. Secure identification of stochastically excited pulsations in the semiregular variables would therefore evidently be of substantial interest.

The present study is of a statistical nature. To confirm our suggestion a more detailed analysis of individual stars, including careful modeling of the stellar structure and the properties of the oscillations, will be required, furthermore using the frequencies to constrain the overall properties of the stars. Also, further observational data should be sought, making full use of the AAVSO data archive, and of other similar archives of long-term observations. Indeed, the century-long data series available for a number of stars in the AAVSO archive are now being validated and quality controlled; these full datasets will then be submitted to the same type of analysis as reported here. To

obtain additional observations of these long-period variables will clearly be a long-term project, although one definitely worth undertaking. However, it is also of evident interest to study similar variations in stars further down the red-giant branch, such as already observed in K giants, of shorter periods. Here the predicted amplitudes are also much smaller, precluding visual observation of the variations. However, with the present trend towards increasing sophistication of amateur equipment, including the extensive use of CCD detectors, there is little doubt that amateur astronomers will be able to continue and extend their very valuable efforts towards providing long-term observations of a nature that are difficult to obtain in a professional setting.

ACKNOWLEDGEMENTS

We are grateful to the numerous observers whose dedicated work forms the basis for the present study. F. P. Pijpers is thanked for useful conversations. We thank C. İbanoğlu for organizing the 1998 NATO Advanced Study Institute in Çeşme, Turkey, where the original idea for this work originated. This work was supported in part by the Danish National Research Foundation through its establishment of the Theoretical Astrophysics Center.

REFERENCES

- Balmforth, N. J. 1992a, *MNRAS*, 255, 603
 Balmforth, N. J. 1992b, *MNRAS*, 255, 639
 Barban, C., Michel, E., Martić, M., Schmitt, J., Lebrun, J. C., Baglin, A., & Bertaux, J. L. 1999, *A&A*, 350, 617
 Bedding, T. R., et al. 2001, *ApJ*, 549, L105
 Bouchy, F., & Carrier, F. 2001, *A&A*, 374, L5
 Brown, T. M., Gilliland, R. L., Noyes, R. W., & Ramsey, L. W. 1991, *ApJ*, 368, 599
 Brown, T. M., Kennelly, E. J., Korzennik, S. G., Nisenson, P., Noyes, R. W., & Horner, S. D. 1997, *ApJ*, 475, 322
 Buzasi, D., Catanzarite, J., Laher, R., Conrow, T., Shupe, D., Gautier III, T. N., Kreidl, T., & Everett, D. 2000, *ApJ*, 532, L133
 Chang, H.-Y., & Gough, D. O. 1998, *Sol. Phys.*, 181, 251
 Chaplin, W. J., Elsworth, Y., Howe, R., Isaak, G. R., McLeod, C. P., Miller, B. A., & New, R. 1997, *MNRAS*, 287, 51
 Christensen-Dalsgaard, J., & Frandsen, S. 1983, *Sol. Phys.*, 82, 469
 Cummings, I. N., Hearnshaw, J. B., Kilmartin, P. M., & Gilmore, A. C. 1998, in *ASP Conf. Ser. 135, A Half-Century of Stellar Pulsation Interpretation: A Tribute to Arthur N. Cox*, eds P. A. Bradley, & J. A. Guzik (San Francisco: ASP), 213
 Edmonds, P. D., & Gilliland, R. L. 1996, *ApJ*, 464, L157
 Foster, G. 1995, *AJ*, 109, 1889
 Gilliland, R. L., et al. 1993, *AJ*, 106, 2441
 Houdek, G., Balmforth, N. J., Christensen-Dalsgaard, J., & Gough, D. O. 1999, *A&A*, 351, 582
 Innis, J. L., Isaak, G. R., Brazier, R. I., Belmonte, J. A., Palle, P. L., Roca Cortes, T., & Jones, A. R. 1988, in *ESA SP-286, Seismology of the Sun & Sun-like Stars*, eds V. Domingo, & E. J. Rolfe (Noordwijk: ESA), 569
 Kjeldsen, H., & Bedding, T. R. 1995, *A&A*, 293, 87
 Kjeldsen, H., Bedding, T. R., Frandsen, S., & Dall, T. H. 1999, *MNRAS*, 303, 579
 Kjeldsen, H., Bedding, T. R., Viskum, M., & Frandsen, S. 1995, *AJ*, 109, 1313
 Kumar, P., & Goldreich, P. 1989, *ApJ*, 342, 558
 Kumar, P., Franklin, J., & Goldreich, P. 1988, *ApJ*, 328, 879
 Martić, M., et al. 1999, *A&A*, 351, 993
 Mattei, J. A., Foster, G., Hurwitz, L. A., Malatesta, K. H., Willson, L. A., & Mennissier, M.-O. 1997, in *ESA-SP 402, Proc. ESA Symposium: Hipparcos – Venice '97*, eds B. Battistich, M. A. C. Perryman, P. L. Bernacca, & K. S. O'Flaherty (Noordwijk: ESA), 269
 Merline, W. J. 1998, in *ASP Conf. Ser. 135, A Half-Century of Stellar Pulsation Interpretation: A Tribute to Arthur N. Cox*, eds P. A. Bradley, & J. A. Guzik (San Francisco: ASP), 208
 Schou, J., & Buzasi, D. L. 2001, in *ESA SP-464, Helio- and Asteroseismology at the Dawn of the Millennium: Proc. SOHO 10 / GONG 2000 Workshop*, (Noordwijk: ESA), 391
 Smith, P. H., McMillan, R. S., & Merline, W. J. 1987, *ApJ*, 317, L79
 Stein, R. F., & Nordlund, Å. 1998, in *ESA SP-418, Structure and dynamics of the interior of the Sun and Sun-like stars; Proc. SOHO 6/GONG 98 Workshop*, eds S.G. Korzennik, & A. Wilson, (Noordwijk: ESA), 693
 Stein, R. F., & Nordlund, Å. 2001, *ApJ*, 546, 585
 Whitelock, P., Marang, F., & Feast, M. 2000, *MNRAS*, 319, 728